VLBI TRACKING OF THE PHOBOS SOIL MISSION

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ABSTRACT

The Phobos Soil, also known as Phobos-Grunt or Phobos Sample Return mission, will begin on October-November 2011 for a three-years mission to explore the Martian system. The robotic craft will land on the Martian moon of Phobos to collect a sample of its soil and bring it back to Earth. A network of radio telescopes coordinated by the PRIDE (Planetary Radio Interferometry and Doppler Experiment) team will conduct multidisciplinary experiments by means of determining the state vectors of the spacecraft with high accuracy using advanced VLBI tracking techniques. The measurements, among other applications, will help to characterize parameters of the Phobos gravitational field.

The accuracy on the estimates of the state vectors depend on the quality and power of the transmitted signal, the observing system resolution and system noise. Based on the latest experiments with operational spacecraft, tracking of Phobos Soil is feasible with accuracy better than cm/s in radial velocity and 50m in lateral positions. In this paper, we report on the status of preparation to VLBI experiments with the Phobos Soil mission and recent PRIDE observations of the European Space Agency's (ESA) Venus Express (VEX) and Mars Express (MEX) missions.

1. INTRODUCTION

One of the most ambitious projects initiated by the Russian Federal Space Agency (ROSCOSMOS) in the past years has been the Phobos Soil mission, also commonly known as Phobos-Grunt or Phobos Sample Return mission. The Phobos Soil probe will be launched using the Zenit rocket from Baikonur, Kazakhstan. The current schedule for the 3-yearlong mission assumes the launch in October- November 2011 ballistic window and the arrival time to the Martian system ten months later. The return of the mission to Earth is expected in August 2014 [1]. The Hayabusa spacecraft [2], developed by the Japanese Aerospace Exploration Agency (JAXA), demonstrated a successful return of a deep space probe and asteroid soil sample after the encounter with a near-Earth asteroid (25143 Itokawa) in June 2010.

The primary goal of the Phobos Soil robotic mission is to collect a soil sample from the Phobos surface and to return it back to the Earth. During its areocentric phase, the mission will also conduct a broad variety of experiments aimed at studies of the origins of the Martian system and its evolution. In February 2013, the Phobos Soil craft will perform a controlled descent and landing on the Phobos surface. Within a month, a soil sample limited to 200 g will be taken from the surface and stored in the return capsule. In March 2013 the return vehicle with the capsule will lift-off from Phobos for a home journey. The return vehicle is expected to arrive to Earth one year after departure from Mars. In addition to its prime goal, the Phobos Soil will act as well as a transportation means for the first Chinese deep space probe Yinhuo-1 (YH-1, "Fairfly"). The landing platform will be equipped with the X-band radio beacon.

European VLBI Network (EVN) of radio telescopes, among others, will perform VLBI tracking of all Phobos Soil mission spacecraft. In the course of the preparations, we have conducted several observing campaigns with already operational spacecraft at X-, S- and UHF-bands. The goal of these observations was to optimise the data processing pipeline from the observation to the analysis and interpretation.

In this paper we are going to by describe the relevant parameters for tracking the Phobos Soil spacecraft. This description is given in comparison with the ESA's Venus Express (VEX) mission most extensively observed in our campaign of 2009-2011. The VEX experiments enabled us to develop and debug special software for processing the narrow band S/C signal and broadband correlation of background natural celestial radio sources This activity has been conducted in the framework of the PRIDE, a generic suite of VLBI-based radio science experiments with deep space missions. The VLBI tracking results presented here allowed us to estimate the precision of the future PRIDE-Phobos experiments.

2. VLBI TRACKING OF THE PHOBOS SOIL SPACECRAFT

Measurements of the Phobos Soil spacecraft state vectors and the position of the lander will lead to estimates of the parameters of the Phobos and Mars gravitational field. In turn these estimates will help to address the enigmatic question of the nature of Phobos and shed some light into the quest of the origins and evolution of the Solar System. This experiment will be conducted with the EVN radio telescopes in collaboration with the Centre for Deep Space Communication in Evpatoria, Ukraine. PRIDE was conceived to provide ground support from radio astronomy telescopes to the upcoming deep space missions launched by the ESA.

Several antennas have contributed during the last two years, and will continue in the future, conducting single-dish and VLBI spacecraft observations. Among these radio telescopes should be remarked: Metsähovi Radio Observatory (Aalto University, Finland), Medicina and Noto Radio Observatories (INAF-IRA, Italy), Matera Observatory (ASI, Italy), Wettzell Geodetic Observatory (BKG, Germany), Radio Astronomy Observatory Yebes (OAN-IGN, Spain), Pushchino Radio Astronomy Observatory (LPI-RAS, Russia), Onsala Space Observatory (OSO, Sweden), Hartebeesthoek Radio Astronomy Observatory (HartRAO, South Africa), Badary Radio Astronomical Observatory (Russia) and Zelenchukskaya Radio Astronomical Observatory (RATAN, Russia). Table 1 shows several parameters of the telescopes involved in PRIDE-VEX observing campaign. The sensitivity of a telescope is expressed in terms of the System Equivalent Flux Density (SEFD), which is the flux density of a hypothetic celestial source that would result in the antenna output equal to the system noise (measured in Janskys (Jy); 1 Jy = 10^{-26} W m^{-2} Hz^{-1}). The lower the SEFD value is, the more sensitive the telescope is.

	Latitude Longitude	**Altit. (m)**	**Da. (m)**	**SEFD (Jy)**
Metsähovi	24°23'35'' 60°13'04''	75	14	3200
Medicina	11°38'49'' 44°31'14''	57	32	320
Matera	16°42'14'' 40°38'58''	543	20	3000
Noto	14°59'20'' 36°42'34''	143	32	770
Wettzell	12°52'39'' 49°08'42''	669	20	750
Yebes	-3°05'22'' 40°31'27''	998	40	200
Pushchino	54°49'20" 37°37'53"	150	22	3000
Onsala	11°55'39'' 57°23'47''	33	20	1380
Hartebeesthoek	27°41'05'' -25°53'14''	1415	26	700

Table 1: Summary of the main characteristics of several EVN radio telescopes: coordinates of the station, diameter of the dish and the SEFD of the antenna at X-band.

The VLBI and Doppler spacecraft technique is similar to the Delta Differential One-way Ranging (Delta-DOR) to resolve its state vectors, as have been successfully demonstrated in a number of deep space missions, although does not require a special on-board equipment and can harvest eventually any signals from the spacecraft, provided it has enough power and phase stability. Among these precursor experiments outstand the ground-based radio tracking of the VEGA balloon for determination of the wind field in the atmosphere of Venus [3], the radio tracking with VLBI radio telescopes of the descent and landing of the Huygens probe on the surface of Titan [4-5], the VLBI tracking with EVN antennas of the crash landing of Smart-1 probe on the surface of the moon [6] and special emphasis to the latest results achieved from Venus Express (VEX) VLBI spacecraft observations [7] and the Mars Express (MEX) Phobos-flyby [8] monitored by 3 EVN radio telescopes.

2.1 Considerations for detections of Phobos Soil signal with the EVN radio telescopes.

During the landed phase estimated to last for about one year, the lander will operate in a beacon mode, using

1W 0dBi X-band transmitter, locked to a stable oscillator (Alan variance better than 10^{-13} in 100 seconds). It will transmit a carrier and ranging tones with a separation of ~10 MHz from the carrier. Receiving power level at a distance of ~ 1 AU will be -200 dBW at 32m antenna, thus yielding detection SNR at a level of ~ 4 in 1 Hz 1 s. That's considerably different from what we are observing with VEX, which produces about -160 dBW in a carrier line at 32m aperture and yields the SNR at a level of tens of thousands in 1 Hz 1 s.

To check the system performance at power levels relevant to the Phobos Soil beacon, we performed a detection of the 7th sub-carrier harmonic of VEX spacecraft, which has a power level of -30 dB with respect to the carrier and is separated by 7 MHz from the carrier. For this test we used the 14m Metsähovi telescope, with rather high Tsys (~100K) at X-band. Signal of this -195 dBW per dish sub-carrier harmonic was successfully detected at 3 s integration and 0.15 Hz tracking bandwidth. Stochastic phase noise of the detection is 0.4 radians in 3 seconds, and Doppler noise is a level of 11 mHz in 3 seconds for a -35 dB tone and 3 mHz for the carrier. On global baselines, the 0.4 radian detection phase noise will correspond to positioning accuracy of ~ 40 meters at a distance of 1 AU, and Doppler noise will correspond to the 0.5 mm/s radial velocity error at a sampling time of 3 seconds. Results of this test are presented in Fig. 1 and show that detection accuracy is mostly dominated by scintillations due to the interplanetary plasma and not by the system noise of the telescope at given power levels and observing conditions.

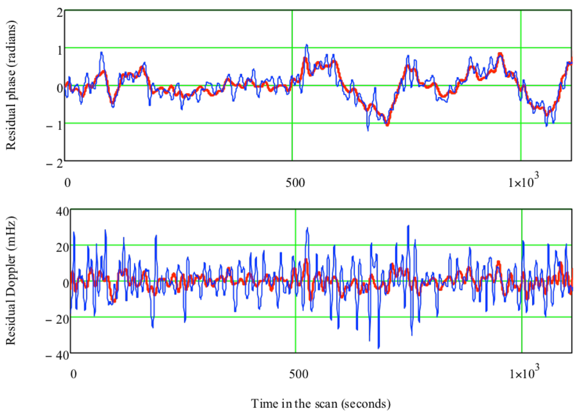

Figure 1: the residual phase and Doppler noise for the -165 dBW carrier line (red trace) and -195 dBW sub-carrier harmonic (blue trace) signals, as detect with Metsähovi on 2011.03.25, using a -30dB sub-carrier harmonic as a test signal. The test mimics the expectation of the PhG beacon detection.

3. DOPPLER VLBI TRACKING SOFTWARE AND SFXC CORRELATOR

In VLBI phase referencing, the relative position of a specific source is determined by observing a known source near-by, known as *phase reference source,* and applying its detected fringe phase values to the target. The most accurate measurements from the source can be achieved by having the source and the calibrator in the same beam or not more than few degrees apart [9]. VLBI phase referencing for spacecraft tracking observes alternatively the RF signal from the spacecraft and a near-by calibrator, most commonly a quasar. The optimal switching time between both sources ranges from tens of seconds to several minutes. The scan duration on each source depends primarily on the efficiency of the antenna, the system temperature and the slewing speed. In our observations, we use scan duration equal to 2-5 minutes, although antennas with faster slewing speed will contribute to increase the switching between sources and thus improve the accuracy of the spacecraft tracking measurements.

The down-converted observed signals are recorded onto the standard VLBI recording systems MarkV A/B [10], developed by MIT/Haystack, or the PC-EVN, developed by Metsähovi radio observatory [11]. Both systems were designed exclusively to record the formatted data for astronomic and geodetic VLBI observations. The VLBI recording systems allow high-data rate ranging from 128 Mbps to 2 Gbps. The large stored data files (17 to 34 GigaBytes) are electronically transferred using fast network connections to Metsähovi and JIVE for the data processing. For those stations with a limited network connection (< 100 Mbps), the disk pack modules are shipped using standard postal service. In order to achieve ultra-fast results from the observations we assume that stations are linked to the processing node with at least 1Gbps fibre optic connection.

3.1 SWspec and SCtrack software kit

The software tools to process and analyse the narrow band spacecraft tones were developed at Metsähovi radio observatory in collaboration with JIVE [12]. The tools are written in C++, available under GPL license, and Matlab code. A python-GUI interface was developed to help configuring the tasks and parameters of the software. A block diagram summarizing the programs, the input and output of the files and the main core processes is shown in the Fig. 2.

The high-resolution spectrometer software (*SWspec*) allows initial detection of the carrier tone of the spacecraft and temporal evolution of its frequency over

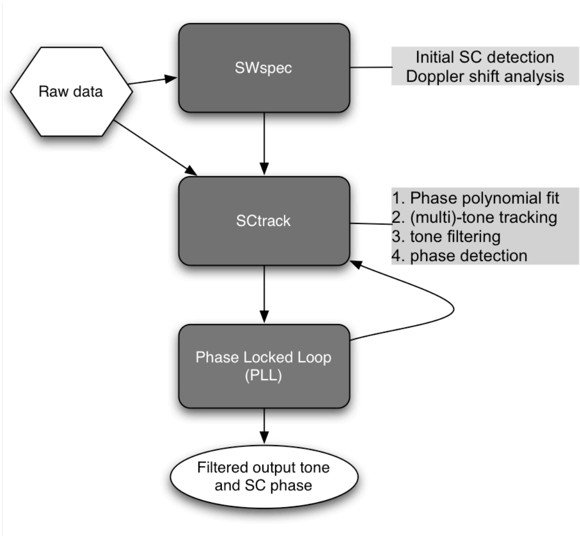

Figure 2: The block diagram for the spacecraft detection software pipeline is shown. The processing pipeline is based on three main programs: the software spectrometer, the spacecraft tracking and the Phase Locked Loop. Tasks 2 to 3 can narrow down the analysis bandwidth much as user requires.

the entire scans. Each SWspec pass extracts one of the raw data channels from the input data file. It performs accurate windowed-overlapped discrete Fourier transform (DFT) and time integration of the spectrum. Finally, all the time-integrated spectra are written to disk for the next iteration. Length of the DFT can be as long as 10 million samples and depends on the Doppler acceleration, practically yield in several Hz spectral resolution over 8 or 16 MHz wide band.

The SWSpec parameters are totally configurable and the software can be flexibly adjusted to the different observations modes. The user can select the initialization parameters such as input data format, number of FFT's to integrate, spectra integration time for the FFT, bandwidth of observations, number of frequency channels and type of windowing. Simultaneous analysis of two circular polarizations (with cross-polarization option) is also available, which is essential for Phobos Soil observations because it will transmit in linear polarization while the telescopes are equipped with circular polarization receivers. Additionally, SWspec can extract the phase frequency of the Phase Calibration (PCal). PCal is a well-known frequency signal injected into the analogue receiver chain at the telescope to determine instrumental phase drift. VLBI groups broadly use this technique as a monitoring utility.

The generated time-integrated spectra are processed using Matlab scripts to determine the moving phase of the S/C tone frequencies along the scan. The series of frequency detections of the carrier line are fitted to a sixth order phase stopping polynomial. The phase polynomial fit is calculated using a Weighted Least Mean Square (*WLMS*) algorithm. The weights (WSNR) depend on the SNR level of the detection, near-by radio interference (*RFI*) considerations and geo-center approximation from the carrier bin. The phase polynomial fit is calculated as:

$$P(t) = 0 + Cpp_{(1)} \cdot t^{1} + \ldots + Cpp_{(M-1)} \cdot t^{(M-1)} \qquad (1)$$

where the phase stopping polynomials (C_{pp}) are used as input for the next iteration of the software that compensates Doppler shift and filter the tone output.

The core of the spacecraft tone tracking software (*SCtracker*) performs a phase polynomial correction, single and/or multi-tone tracking, signal filtering for each tone and phase detection of the carrier line with respect to the local H-maser clock. The software is initialized using the raw telescope input data, a list of S/C tone frequencies (which can be 0 for single tone or the offset of the sub-harmonics relative to the carrier) and the 6^{th} order phase stopping polynomial coefficients from the previous WLMS fit. The phase and frequency corrections are applied using the phase coefficients to the baseband sample sequence *x[n]* to stop the carrier tone phase by means of a high order polynomial phase synthesizer:

$$\bar{x}[n] = x[n] \cdot \exp\left(\pm i \sum_{k=2}^{M-1} Cpp(k) \cdot T[n]^{k} \right) \qquad (2)$$

where *T* and *Cpp* are the data sample time stamp and the phase polynomials coefficients respectively.

The output of SCtracker generates the time-integrated windowed-overlapped spectra of the stopped baseband signal, the relative phase derived from the carrier tone and the narrow band extracted from the stopped baseband signal around each of the specific tone frequencies. For convenience, a decimation ratio of 1:4000 is used, resulting with a narrow bandwidth of 2 kHz. The series of extracted bands are properly filtered out into continuous complex time-domain signals with a bandwidth ≤ 4 kHz using a 2^{nd} order Window-Overlap-Add (WOLA) DFT-based algorithm of the Hilbert transform approximation.

The current implementation of software allows a practically unlimited number of narrow bands to be filtered and down-converted, with arbitrary distribution of them in the input band. These narrow bands are written into complex floating-point output files and they are the basis to the next iteration of the process.

The final post-analysis of the narrow-bands is called the Phase-Lock-Loop (PLL) software. The software is written both in Mathcad (developed at JIVE) and Matlab (recently implemented at Metsähovi). The PLL runs high precision iteration of the phase polynomial fit on the filtered complex narrow-band signals (i.e. Equations 1-2). The implementation of the PLL allows filtering down the tones as many times as desired in order to achieve mHz accuracy around the spacecraft carrier line or other tones in the band. The final residual phase in a specific stopped band is determined with respect to the set of subsequent frequency/phase polynomials initially applied.

3.2 Software Correlator

The SFXC (Software FX Correlator) [13] VLBI software correlator is being developed at JIVE to replace the old Mark IV hardware correlator [14] and is currently used as a production correlator for astronomical observations with the EVN. SFXC is based on the original design developed for the VLBI tracking of the Huygens probe [5] and is capable of supporting both the far field and near field models.

Several VLBI observations of spacecraft were correlated with the SFXC at JIVE using a near field theoretical delay model. More information about near field and far field models is detailed in the next section. SFXC is used to correlate both the far field phase referencing calibrators and near field spacecraft signals.

3.3 Near-field delay model

The phase solutions after the correlation of the calibrator are then transferred to the processing results of the spacecraft signal. Because of the different nature of both sources two different delays models are required. For calibration sources located at large distances, the *far field* or also known as *consensus model* [15] is used. For the spacecraft, at relatively closer distances, the *near field* model developed by Sekido-Fukushima is selected [16]. The near field theoretical delay model has been implemented at JIVE [17,18] as a Matlab code and will be integrated into the SFXC operational environment.

The topocentric measurements of the frequency and phase of the S/C signal at each station are reduced to the common phase centre, commonly to the *geocenter*. The Sekido-Fukushima model computes the geometrical part (in the general relativity metric sense) of the delay by introducing a pseudo source vector to compensate the effect of the curved wave front and by using Halley's method up to the second-order to correct the variation of the baseline vector due to differences in the arrival time. The theoretical precision of the model is better than 1 psec for radio sources at distances more than 100 km above the Earth. Besides of geometrical correction, contributions to the signal delay from troposphere, ionosphere and clock offset at the stations are also included.

4. VEX RESULTS

Since the year 2009 we have been constantly working on developing the new spacecraft detection software and testing its capabilities in a large number of different scenarios:

- Single-dish S/C sessions.
- Simultaneous multi-station S/C sessions.
- VLBI S/C tracking sessions.

The single-dish S/C observations started as test sessions to evaluate the potential of the radio telescopes and the new developed software to detect the S/C signal and moved towards the study of the phase fluctuations on the S/C signal caused by propagation along the path and the Interplanetary Plasma Scintillation (IPS). The latest has been presented in [7,19] and the results are updated in the section 4.2. During these observations the S/C signal was recorded using six to nine 19-minutes scans. For the IPS studies the sessions were widely distributed along the year to maximise the coverage of phase scintillation with respect to the solar elongation of the target. Another premise was to use as wide range of radio telescopes as possible to learn the peculiarities for each station and check for possible biases between them.

Simultaneous multi-station S/C tracking sessions using two or more EVN radio telescopes allow comparing the frequency/phase detections at each station. Therefore, the carrier tone, the respective sub-harmonics and the residual phase can be determined as seen via two different Fresnel channels. It is also a good test for trouble-shooting at the antenna and receiving systems, since data can be easily compared from both sites.

Finally, in VLBI S/C tracking sessions, the observations of the RF signal are alternated with a strong known calibrator source. To determine the true capabilities of VLBI tracking for future planetary probes orbiting other planets in the Solar System, it is necessary to demonstrate the accuracy of our detection for the existing spacecraft. Thus, several multi-station VLBI experiments have been conducted during the last year. The latest, *em081c*, has been the most intensive experiment until now with regards to the number of participant telescopes.

4.1 Tracking of Venus Express on the 25th and 28th March 2011

On the 2011.03.28 we arranged the largest attempt of VLBI Venus Express tracking observation. The initial plan for the *em081c* included eleven radio telescopes from the EVN network plus the NRAO Very Large Baseline Array (VLBA) station St. Croix. The session was a continuation for the previous observations *em081a*, conducted on the 2010.08.23 with 4 stations, the *em081b*, conducted on the 2010.09.20 involving 5 stations, and the *v110325*, just conducted 3 days before em081c, involving 4 radio telescopes. In the em081c session, all EVN radio telescopes were configured to observe alternatively the phase reference source and the spacecraft signal with a nodding cycle of 4 minutes. At the day of the observation, the radio telescopes participant in the session were: Metsähovi (*Mh*), Onsala (*On*), Matera (*Ma*), Medicina (*Mc*), Yebes (*Ys*), St. Croix (*St, USA*) Hartebeesthoek (*Hh*), Zelenchukskaya (*Zn*, Russia), Svetloe (*Sv*, Russia) and Pushchino (*Pu*). It was the greatest challenges we had to face, including the preparation of the schedules for all stations and process of the large amount of data. Furthermore, three new stations, without any experience of spacecraft tracking sessions, were included in. The 14-metre dish of Fortaleza (*Ft*, Brazil) was supposed to take part in the session, however could not participate due to major technical reparations. Fortaleza will introduce an incredible baseline inside the network and we expect its operability soon.

The em081c session was scheduled on 08:45 until 11:30 UTC, for a total duration of 2 hours and 45 minutes. Each of the nodding cycles was 4 minutes long with 20 seconds gap for re-pointing and antenna calibration. We collected 79 scans per station, divided between 38 of VEX and 41 of the calibrator sources. We used two different phase reference sources during the session: the J2211-1328 (39 scans) with coordinates (Ra/Dec) of 22h11m24.1s -13°52'30.2" and the J2225-0457 (the first and last scan) with coordinates 22h25m47.2s -04d57'01.4". The VEX spacecraft had mean coordinates of 22h14m13s -11d41'22''. At the time of the observations Venus was at a solar elongation of 36 degrees and a distance from Earth of 1.23 AU. The Fig. 3 and Fig. 4 show the major parameters of the VLBI array: the *UV* coverage and the shape of the synthesized beam. Note the granularity of the beam: central core is ~ 1 milliarcsecond (*mas*) wide and surrounded by side lobes with ~ 1 mas separation.

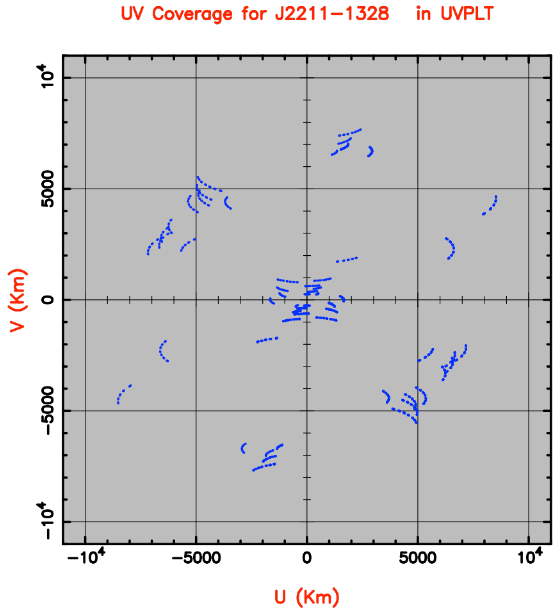

Figure 3: coverage in the UV plane (in km) for the source J2225-0457. The UV coverage was simulated using the same array of participating in em081c. The max baseline in direction E-W is 8500 km and N-W is 7800 km.

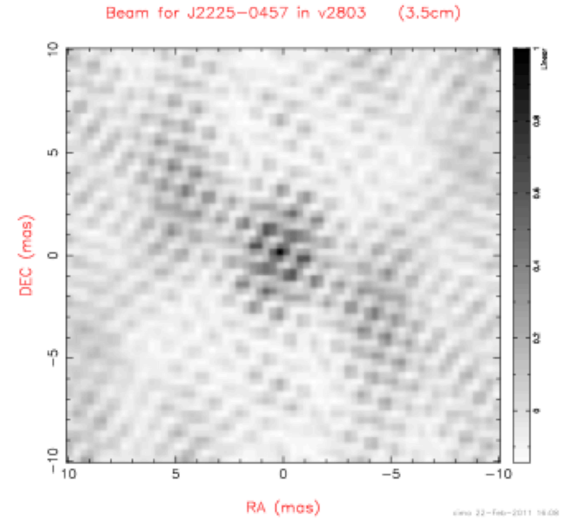

Figure 4: synthesized beam for the source calibrator J2225-0457 in X-band (3.5 cm). The simulation was made using the radio telescopes involved.

Data was acquired using the standard VLBI data acquisition system based on Mark5 A/B recording equipment. We used four 16 MHz wide band channels with 2-bit Nyquist sampling, achieving a total of 256 Mbits per second aggregate data rate per each station. Data files were either transferred over the fast network connection after the experiment to Metsähovi in Finland or shipped via postal service to the processing site at JIVE in The Netherlands. Using real-time recording and e-transfer, the data processing can start immediately after the end of the session.

The narrow band data from the spacecraft were analysed at Metsähovi with the on-purpose spacecraft software that was explained in detail in the previous section. We are still in the process of analysing all data from the em081c session. Therefore this paper is mainly concentrating on the results of the session v110325 that was performed three days earlier. The observation was conducted with the radio telescopes of Metsähovi, Onsala, Hartebeesthoek and Pushchino. The frequency detections measured on the 2011.03.25 for the four radio telescopes are shown in the Fig. 5. The Doppler frequency detections show a robust pattern between On, Mh and Pu; the frequency detection differs by several kHz between each station.

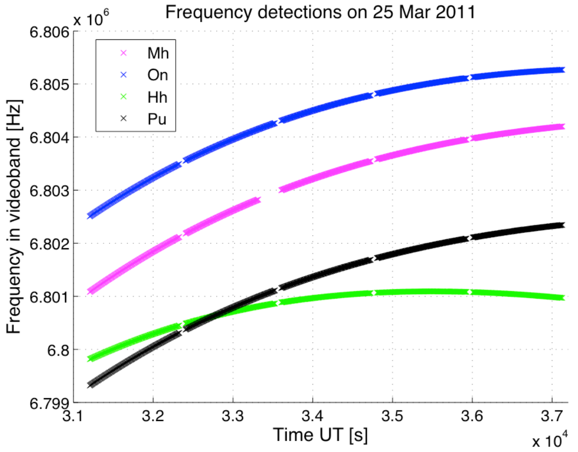

Figure 5: topocentric frequency detections observed at Onsala (blue), Metsähovi (magenta), Hartebees-hoek (green) and Pushchino (black) on the VEX session on 2011.03.25.

We processed the data from the four radio telescopes using first the SWspec, then SCtracker and finally several iterations of the PLL. The last iteration of the PLL narrowed the signal to 1 Hz band around the carrier line with 0.2 Hz spectral resolution and allows us to extracts the phase of the signal. The Doppler frequency residuals from the VLBI radio telescopes and the phases extracted at On and Mh are shown in the Fig. 6 and 7, respectively.

Problems with the local oscillator at Pu and Hh caused an excessive variance of the measured Doppler residuals. Thus, the phase of the VEX signal could not be extracted from the data of either station. At Mh and On the level of the Doppler residual is much lower (within 20 mHz boundaries), which made it possible to measure the S/C phase. The 2nd scan shows strong RFI, which the origin is still undetermined, that invalidates its results, the origin of this problem. The extracted phase for VEX signal at On and Mh show strong correlation in all the scans. To improve the readability of the plot we added and subtracted 1 rad from data set. An exception is seen in the last scan, where the phase at Mh is masked for a strong phase variation. The post-analysis of the phase fluctuations can isolate and filter such undesired breaks in. This post-analysis is also useful when the data is used for characterising the interplanetary plasma contribution on the signal's phase.

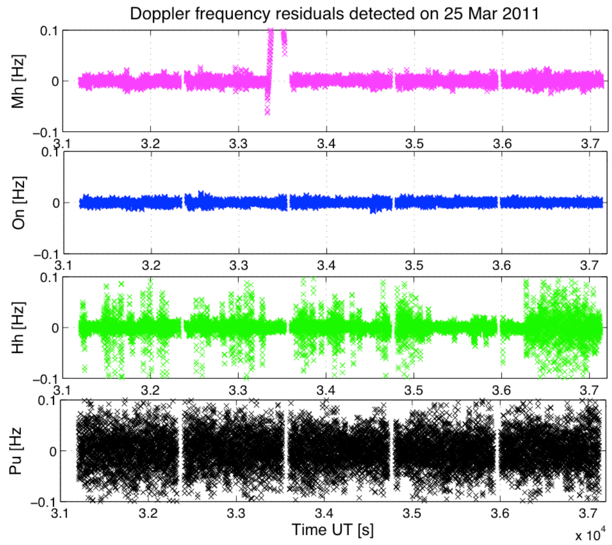

Figure 6: Doppler residuals detected at Onsala, Metsähovi, Hartebeeshoek and Pushchino on the VEX session on 2011.03.25. High phase noise was presented in the last two antennas.

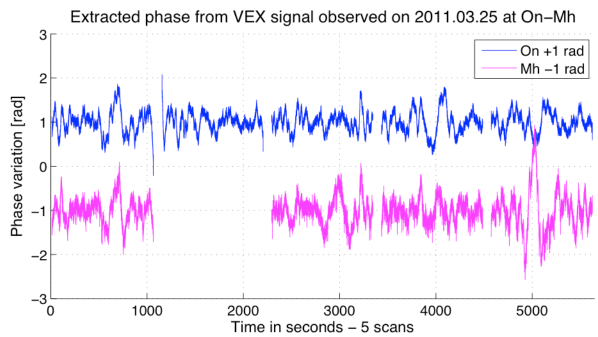

Figure 7: Phase detected at Onsala and Metsähovi on the VEX session on 2011.03.25. The 2nd scan from Mh was not useful.

The broadband correlation results were processed at JIVE using the SFXC software correlator [13] and the Astronomical Image Processing System (AIPS) software [20]. The time elapsed between the observation and the results of the correlation depend on the availability of the correlator. With the old hardware correlator the results usually take up to several weeks but the new SFXC correlator can potentially decrease significantly the processing time. Real-time sessions are able to produce results in just few hours after the data transmission is complete. The Fig. 8 represents the cross-correlation spectrum of the VEX signal (amplitude and phase) on a baseline On-Mh, as observed on 2011.03.25.

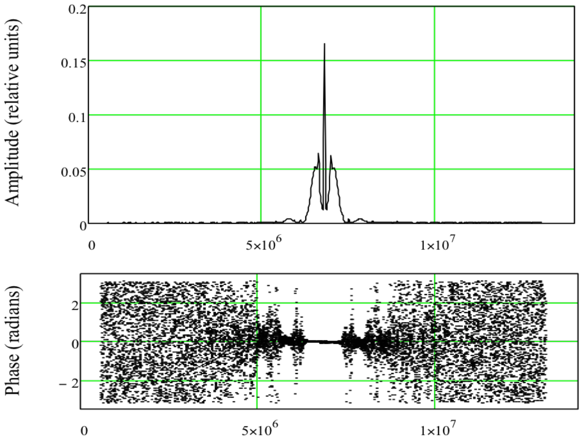

Figure 8: Cross-correlation spectrum (amplitude and phase) of the VEX signal on a baseline Onsala-Metsähovi observed on VEX 2011.03.25

Most of the spectral power is concentrated in ~1 MHz region around the carrier line, but this frequency spread at such high SNR is enough to resolve the 2π ambiguity between the group delay detected by the broad band correlation with the SFXC and phase delay detected using the SCtracker software.

The correlation of the calibrator source for each baseline provides the residual delays. To apply coherently the phase referencing, the residual delays must be lower than the radio wave period at X-band, e.g. 0.120 ns. The measured residual delays and phases are then applied to detected residual phases of the target. Calibrated residual phases are used then to recover the deviations of the lateral coordinates of the target with respect to a-priory ones. The Fig. 9 shows the expected lateral coordinates dA/dB (mas) of the VEX spacecraft position. The dA/dB scatter plot presents the lateral coordinates (dRa/dDec) after rotating the coordinate system to align it with the principle axis of the system beam and reduce the covariance between coordinate deviations. The simulation result plotted here, takes into account the usage of a network of radio telescopes, at least, as wide as it was used in the em081c session.

4.2 Interplanetary plasma scintillations

Phase scintillations of the spacecraft signal on the electron density fluctuations of the interplanetary plasma is one of the main factors limiting the accuracy of VLBI observations of spacecraft. Regular monitoring of the phase scintillations of VEX signal at different stations and different solar elongations is helpful to optimisation of detection technique and to debug possible problems at observing stations. On the other hand, the study of the phase fluctuations of the spacecraft carrier line is used to characterise the interplanetary plasma along the propagation path. During the two years of research more than 60 observations have been performed studying the propagation of the VEX spacecraft signal. In this exercise, the phase scintillation index and scintillation bandwidth were retrieved from the phase fluctuations. The phase scintillations have shown direct dependency

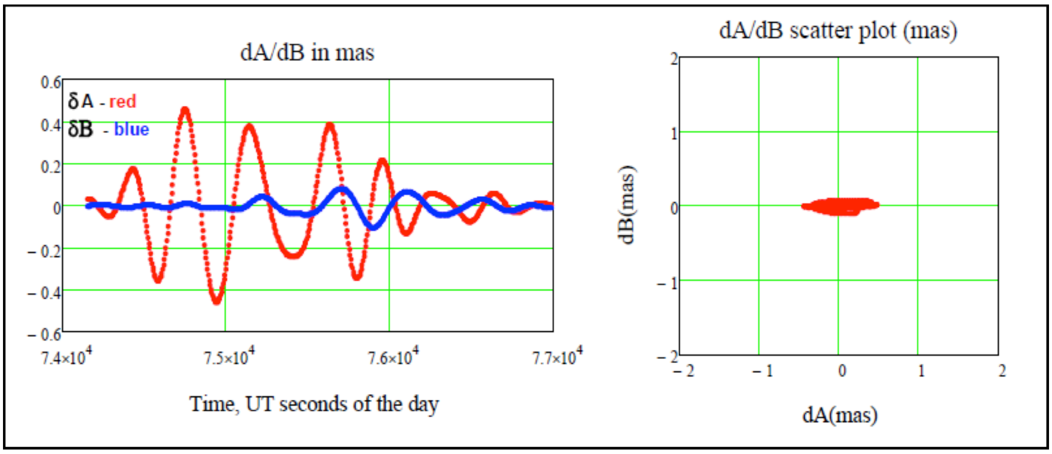

Figure 9: Expected lateral coordinate deviations (dA/dB) (in millarcseconds) of the VEX spacecraft a-priori position, along the principal axes of the system beam, using 4 minutes nodding cycle, projected to the plane of the sky. RMS of deviations is 0.19 mas and 0.035 mas for A and B axis correspondingly, what is the same as 170 m and 30 m in linear measure with respect to the nominal state vectors. Data was simulated using data from past experiments.

on the solar elongation, distance to the target, position of the source within the Solar System and solar activity index at the time of the observations. This work was focused on the technique of the measurements, data analysis and the interpretation of the physical consequences of the measurements.

The IPS is characterised as the variation in the apparent power density and phase of a radio signal propagated through the solar wind plasma. The density of the fluctuations in the solar wind is associated to strong turbulences in the medium. These resemble the well known hydrodynamic turbulence described by Kolmogorov in 1941 [21]. The phase scintillation spectra observed in our detections are well represented by a near-Kolmogorov spectrum. The Fig. 10 and 11 shows an example of the phase fluctuations and phase scintillation spectrum from the data observed at Onsala on the 2011.03.25 experiment.

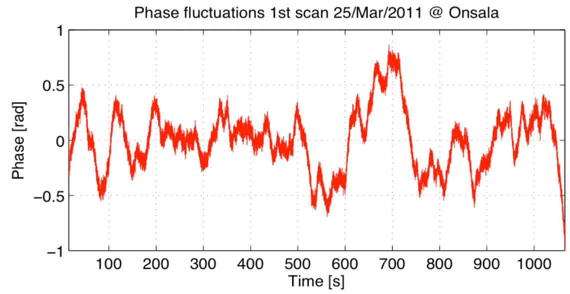

Figure 10: the phase fluctuation observed on the first scan 2011.03.25 at Onsala. Low level of fluctuations due to the large solar elongation of Venus is shown.

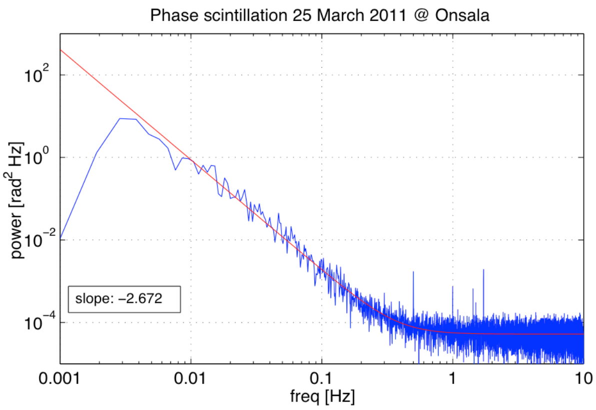

Figure 11: the phase scintillation spectra observed on 2011.03.25 with the radio telescope of Onsala is shown. The scintillation slope is -2.672. The spikes above 0.5 Hz frequencies are caused by RFI.

The analysis of all data accumulated has allowed us to study the phase scintillation dependency on the solar elongation, distance to the target and the direct relation between the phase scintillation RMS and solar elongation, among others. Fig. 12 shows the projection of the phase scintillation RMS with respect to the solar elongation (in degrees), also known as Sun-Observer-Target (SOT), over the Total Electron Content (TEC) of the solar wind at a nominal density of 5*cm^{-3} at 1 AU distance from Sun. The results include all the samples obtained during the last 18 months of observations.

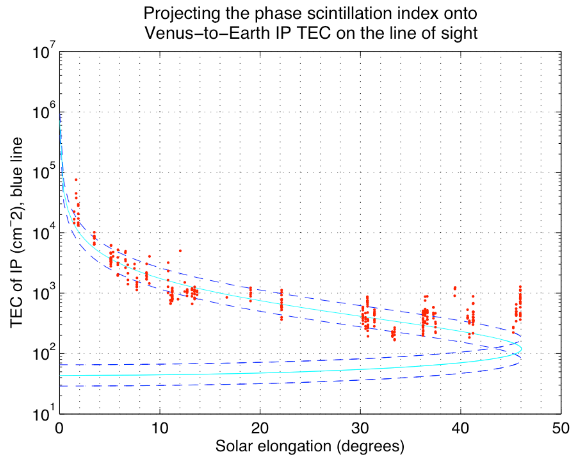

Figure 12: shows the projection of the phase scintillation RMS index onto the Venus-to-Earth interplanetary TEC on the line of sight. The data include all the 57 sessions conducted until May 2011.

The estimation of the TEC along the path Earth to spacecraft can be calculated as a function of the Sun-Observer-Target position. The electron density at certain point depends on its distance with respect to the sun. We can assume the following dependence of the electron density from the distance to Sun, Eq. 3:

$$n(r) = n_0 \cdot \left(\frac{r_o}{r}\right)^2 \tag{3}$$

where $n(r)$ is the electron density at a distance r from the Sun and n_0 is the nominal electron density of 5 cm^{-3} at a distance r_0 of 1 AU from the Sun. Then, the TEC for the observer-spacecraft path is estimated as the integral of the electron density through its propagation path, Eq. 4:

$$TEC = tecu^{-1} \int_{Earth}^{VEX} n(r(l)) \cdot dl \tag{4}$$

where *tecu* is the unit of electron content per a square meter and is equal to 10^{16} m^{-2}, and n is the electron density at any point along the path (S/C – Earth) with respect to the Sun.

CONCLUSIONS AND FUTURE WORK

Starting on summer 2012 the PRIDE team will face up the challenge to detect and estimate the state vectors of the Phobos Soil probe and the robotic craft using the EVN radio telescopes. Detections of sub-carrier harmonics relative to the VEX carrier signal have demonstrated that our software can cope with the low constraints imposed by the Phobos Soil X-band transmission channel. The detection of the signal is ensured even with the smaller radio telescope dishes of the EVN, such as the Metsähovi radio telescope in Finland. The work now is focussed on optimising the observation and the processing pipeline.

In the meantime, observations of the VEX spacecraft will continue frequently for the rest of the year, with the aim of completing the cycle of observations based on the full orbit of Venus around the Sun. The success on the performed sessions helps us to encourage new stations to join the project. Indeed, the number of participant radio telescopes has doubled since the presentation of the previous paper at IPPW-7 [5]. The PRIDE team is confident to enhance our VLBI tracking approach to new interesting events that can take place almost anywhere within the Solar System, as shown with the Mars Express Phobos-flyby [5]. However, the aim is not exclusively oriented to planetary probe mission, but to satellites orbiting in the Earth as well, as it was demonstrated with VLBI observations of GLONASS satellites [22-23].

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ACRONYMS

Dec Declination
DFT Direct Fourier Transform
ESA European Space Agency
EVN European VLBI Network
ICRF International Celestial Reference Frame
IPS Interplanetary Plasma Scintillations
JIVE Joint Institute for VLBI in Europe
Ma Matera
Mc Medicina
MEX Mars Express
Mh Metsähovi
Nt Noto
NRAO National Radio Astronomy Observatory
PCal Phase Calibration tone
PLL Phase Locked Loop
On Onsala
PhG Phobos Soil mission
PRIDE Planetary Radio Interferometry & Doppler Experiment
RA Right Ascension
RF Radio Frequency
RMS Root Mean Square
SEFD System Equivalent Flux Density
SNR Signal to Noise Rate
S/C Spacecraft
SOT Sun-Observer-Target
TEC Total Electron Content
tecu Total Electron Content Unit
Tsys Temperature of the system
VEX Venus Express
VLBI Very Long Baseline Interferometry
Ys Yebes
WLMS Weighted Least Mean Square
WOLA Windowed-Overlapped Add
Wz Wettzell

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